Changes in Mid-Troposphere Snow Accumulation on Mt. Logan, Yukon, over the Last Three Centuries

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ABSTRACT: A net snow accumulation time series is presented. It is derived from a 102.5 m ice core retrieved from Mt. Logan at an altitude of 5340 m a.s.l. Annual increments are identified using stable isotopes, trace chemistry, and beta activity. An absolute time scale is constructed using the chemical signatures of volcanic events. Annual layers are converted to water equivalent using the measured density profile. Corrections are applied for ice deformation and the surface snow accumulation gradient. The resulting time series of nearly 300 years seems to indicate a lower mean accumulation from AD 1700 to the mid-19th century than after that time. The last 100 years of the series correlates significantly with certain instrumental station records at mid-northern latitudes.

INTRODUCTION

In 1980, a 102.5 m glacier core was retrieved from a site at 5340 m on Mt. Logan (60°35'N; 140°35'W; 5951 m), Yukon, Canada. With update to 1987, the core spans almost 300 years. The data are in the form of:

- $\delta^{18}O$ (δD) time series, usually assumed to represent proxy temperature information, and
- The net snow accumulation time series.

To correctly interpret the results, particular attention must be paid to the fact that the core site is located in the middle troposphere above the lower frictional boundary layer. An initial ice flow model time scale for the core was calibrated using the chemical signatures of volcanic events as time markers. Isotopic and certain trace chemical signatures were used to identify seasonal and, hence, annual layers. Beyond the depth where stable isotopes become unreliable (60 m), seasonal signatures are solely identified by nitrate ion variations.

STABLE ISOTOPE TIME SERIES

Vertical profiles of stable isotopes on Mt. Logan and nearby Mt. Steele over an altitude range of 4100 m define the upper limit of the lower boundary layer to be at about 3350 m. Above this is a mixed (iso-δ) layer reaching to the upper plateau at about 5300 m. This mixed layer is evidently created by wind shear, which blends boundary layer moisture with moisture from the free troposphere (geostrophic flow region) that begins at the level of the upper plateau. Upper air wind data have been used to arrive at this interpretation. Vertical variations in this precipitation structure will cause a spurious signal to be built into the $\delta^{18}O$ time series. This will be added to signals due to storm track length variations (Covey and Haagenson, 1984), the rate of delivery of precipitation to the site, and the temperature effect (Dansgaard et al., 1973).

As a result, the time series is difficult to interpret, although sections of it appear to be closely related to air temperature by comparing it with a tree-ring width time series from the northern Yukon (Jacoby and Cook, 1981). This series correlates with regional air temperature. The two dendro-climatological coldest periods virtually coincide with two isotopic minima at ca. AD 1715-1725 and ca. AD 1850-1855. The latter period probably includes the year of "two winters" recorded in Indian legend throughout the Yukon (Cruikshank, 1981). A substantial volcanic acid signal at 70 m depth in the core is believed to correspond to the eruption of Chikurachki-Tartarinov in the Kurile Islands in 1850-1855 (Simkin et al., 1981). In the same way that the "year without a summer" in 1816 was linked (Stommel and Stommel, 1983) to a volcanic event (the eruption of Tambora), it is possible that the "two winters" episode was a result of reduced surface isolation caused by the dust and acid gas cloud from the North Pacific rim eruption in 1853-1855. Paleoclimatic evidence for the "year without a summer" (1816) is not seen in either the Mt. Logan stable isotope record or in the northern tree ring chronology of Jacoby and Cook (1981), even though the acid signal from Tambora is quite clear in the ice core data. These results emphasize the fact that such events may affect only certain regions, rather than being uniformly distributed throughout a hemisphere.

NET ACCUMULATION TIME SERIES

Annual increments identified in the core have been corrected for effects of ice deformation and for an accumulation gradient across the core site. Below a depth of 97 m (AD 1736) annual increments become difficult to define using current methods of sampling. Figure 1 shows the net accumulation time series. It is of great importance to know the reliability of this series before it is used for climatological or hydrological modeling.

An estimated error from AD 1950 to 1987 is 0.01 m. The corrections for ice deformation are negligible until a depth of about 65 m is reached. At this depth, grain

In J.L. Betancourt and A.M. MacKay, editors, 1990. Proceedings of the Sixth Annual Pacific Climate (PACLIM) Workshop, March 5-8, 1989: California Department of Water Resources, Interagency Ecological Studies Program Technical Report 23.

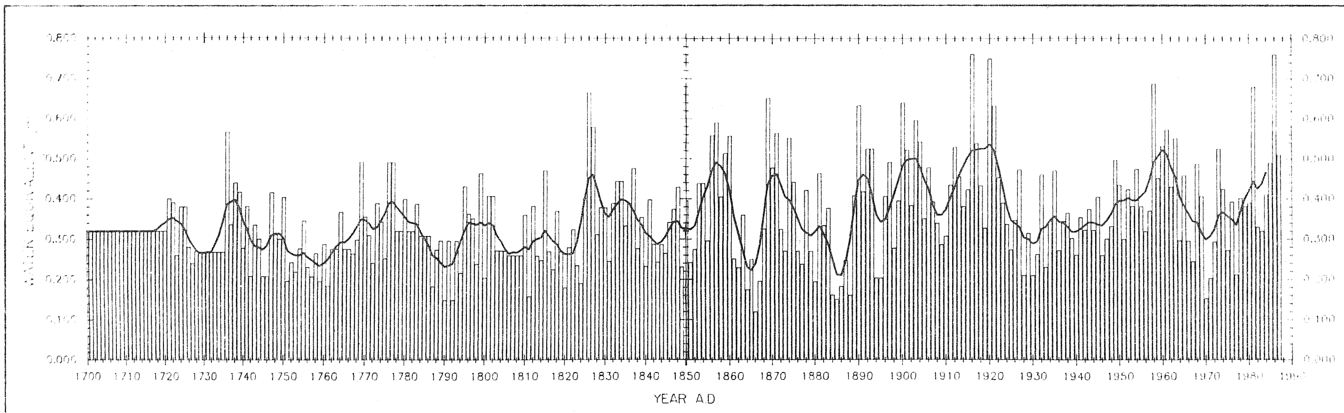

Figure 1. Time series of net snow accumulation, in meters of water equivalent, at 5340 m altitude on Mt. Logan.

compaction and diagenesis have caused layer thinning and have produced "ice" of density 0.83 mg m^{-3}. Further slow densification occurs as the ice flows outward to cause progressive creep thinning of layers. The layer thinning correction, the largest one to be applied, together with corrections for layer tilt and for the gradient of accumulation across the core site, account for a total error of about 0.04 m at a depth of about 101 m (AD 1700). To this must be added the estimated error (0.01 m) for layer misidentification. Thus a total estimated error of 0.05 m applies at the lower end of the series.

Calibration against Instrumental Data

Cross correlation with low level Yukon and Alaska station data yields statistically insignificant results. On the other hand, several significant, positive long-distance correlations (teleconnections) exist. These include parts of the western prairie region of North America, the steppe region of the Soviet Union (Budyko, 1977), and Japan, where the mean of five major station precipitation time series – when compared with the Mt. Logan accumulation series from AD 1890 to 1985 – show a correlation coefficient $r = 0.6$, significant at the 95% level. Such a result may be due to:

- Location of the core site in the middle troposphere,
- Proximity of these sites to the limits of the circumpolar vortex,
- Their proximity to the preferred tracks of Rossby waves, and
- The trajectories of major cyclones.

An ocean/atmosphere interaction is also implied.

Figure 2 shows some elements of the north Pacific climate system that are likely to be responsible for the climate of Mt. Logan. Significant positive correlations between sea surface temperatures and the snow accumulation series exist over extensive peripheral regions of the north Pacific.

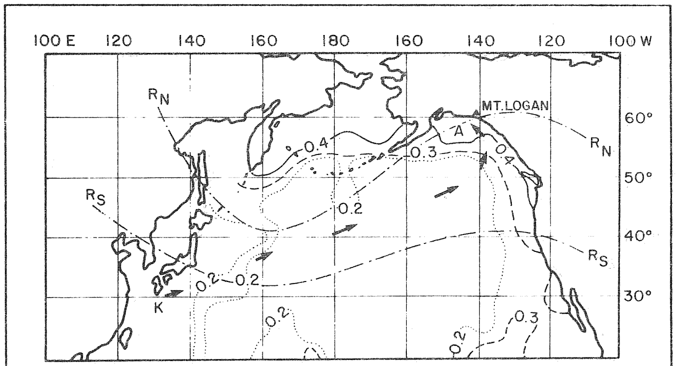

Figure 2. North Pacific sector showing approximate position of the northern and southern limits (R_N, R_S respectively) of the preferred Rossby wave tracks, the Kuroshio current (K), Alaska current (A), and iso-lines of the cross correlation coefficients (0.2 to 0.4) between Mt. Logan net accumulation series and sea surface temperature series.

Spectral Analysis

Power spectra have been produced for the full (250-year) time series and its two halves. Several physically significant peaks occur at frequencies corresponding to periods of 3.8, 10.9, and 15 to 22 years. These periods may be associated with the El Niño/Southern Oscillation (Quinn et al., 1987), the quasi-periodic sunspot cycle, and possibly the lunar M_N tidal period (Currie, 1984) and/or the 20-year period signal of Hibler and Johnsen (1979). The statistical significance of these peaks is marginal at the 90% level, but the integrity of at least the 10.9-year peak has been verified by generating the waveform in the time domain and comparing it with the Zurich sunspot number waveform. For such results to occur, the time scale of Figure 1 must be essentially correct. This implies also that the snow accumulation data are essentially correct.

DISCUSSION OF RESULTS

For the early half of the series, some uncertainty does exist in identification of some individual annual layers; therefore, a safer series would be one produced by using a 2-year filter. The 7-year triangular filter applied to the original data set (Figure 1) more than compensates for the ± 1 year error in occasional layer misidentification.

Two immediate observations can be made:

- The mean net accumulation rate for the early half of the series (0.31 m yr^{-1}) is significantly lower than the corresponding value (0.37 m yr^{-1}) for the more recent half.
- The variance of the early half is significantly less than that of the more recent half.

These changes took place over the latter half of the 19th century, which may coincide with the end of the Little Ice Age (LIA) for this region. According to Denton and Stuiver (1969), late Neoglacial advances in the St. Elias Mountains terminated during this period. Evidence from a drowned forest in Lake Kluane (Bostock, 1969), northeast of the St. Elias Mountains, indicates lake levels were substantially lower during the LIA than now. This implies that snow and ice melt runoff was lower during the LIA than it has been this century. Whereas such a result can be attributed to lower air temperatures during the LIA, it could also be attributed to lower snowfall in the St. Elias Mountains region. This, in turn, can be linked to lower north Pacific sea surface temperatures.

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